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Theoretical Expectations For High Mass Photon Pairs in $l^+l^-\gamma\gamma$ Events at LEP/SLC*

S. Jadach†, B.F.L. Ward and S.A. Yost
Department of Physics and Astronomy
University of Tennessee
Knoxville, TN 37996-1200, USA

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Abstract

Recently, the L3 collaboration has reported the observation of four events in the reactions $e^+e^- \to l\bar{l} + \gamma\gamma$, $l = e, \mu, \tau$, with the invariant photon pair mass near 60 GeV in a data sample collected in the L3 detector corresponding to 950,000 produced Z^0's. More recently, more data from the other LEP collaborations have become available. In this paper, we use the Monte Carlo genrator YFS3 and our recent exact results on $e^+e^- \to l\bar{l} + \gamma\gamma$ to assess the QED expectations for such L3-type high mass photon pair events in $e^+e^- \to l\bar{l} + \gamma\gamma + n(\gamma)$ near the Z^0 resonance.

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†Permanent address: Institute of Nuclear Physics, ul. Kawiory 26a, Cracow, Poland

1 Introduction

Recently, the L3 collaboration reported [1] the observation of high-mass $\gamma\gamma$ pairs in the reactions $e^+e^- \to l\bar{l}+\gamma\gamma$ in the Z^0 resonance region; in particular, four such events were reported with the invariant $\gamma\gamma$ mass near 60 GeV from a data sample corresponding to 950,000 produced Z^0's in the LEP e^+e^- colliding beam device. More recently, related data from the ALEPH, DELPHI, and OPAL Collaborations [2] have become available, and hence, an immediate issue which needs to be addressed is that of the theoretical expectations from the basic QED processes themselves for such high-mass photon pairs. It is this issue which we shall address in what follows.

More specifically, we want to use the YFS Monte Carlo approach [3] to higher-order $SU_{2L}\times U_1$ processes introduced by two of us (S.J.and B.F.L.W.) and the recent exact results [4] by the three of us on the processes $e^+e^- \to l\bar{l}+\gamma\gamma, l = e, \mu, \tau$, in the Z^0 resonance region to assess the probability that the observations in Refs. [1, 2] are consistent with higher-order QED processes. This means that the over-all normalization of our calculations in the L3 acceptance must be known even in the presence of the strong initial state radiative effects associated with the Z^0 resonance line shape. Accordingly, we will employ our YFS Monte Carlo event generator [3], which treats $e^+e^- \to f\bar{f}+n(\gamma)$, in the Z^0 resonance region with the $n(\gamma)$ multiple photon radiation for both the initial and final fermion. Here, f is a fundamental $SU_{2L}\times U_1$ fermion. We should stress that, strictly speaking, $f \neq e$ is implicit in YFS3. However, in the L3 acceptance for the high mass $\gamma\gamma$ pairs, kinematical cuts eliminate any large effect from the exchanges in $e^+e^- \to e^+e^- + n(\gamma)$ which are not the s-channel Z^0 exchange, so that we can use YFS3 for our analysis at the currently required level of precision. Our recent results in Ref. [4] of course do not have any such qualification in their applicability to the L3-type events for $e^+e^-\gamma\gamma$ final states: the full matrix element is available from Ref. [4], and indeed, it will be used to check the validity of our YFS3 s-channel exchange approach to the high $\gamma\gamma$ mass L3-type $e^+e^-\gamma\gamma$ final states, for example.

What we will do in this paper then is to set the QED higher order expectations for the L3-type high $\gamma\gamma$ invariant mass events. We hope that sufficient data will be taken so that the statistical errors on the experimental results analyzed in this paper will cease to be the over-riding dominant error in the comparison between theory and experiment. We encourage the

LEP/SLC experimentalists to strive to accumulate the attendant factor ~ 10 in statistics required to reach this latter goal.

Our work is organized as follows. In the next section, we present some relevant theoretical and experimental background information. In Section 3, we compare our theoretical predictions with the LEP data. In Section 4, we present some summarizing discussions.

2 Preliminaries

The basic framework in which we shall work will be that of the renormalization group improved YFS theory that is realized via Monte Carlo methods via the event generators YFS2, BHLUMI, and YFS3 in Refs. [3]. Since we shall focus on the YFS3 predictions for L3-type events, we begin by describing the relevant aspects of the Monte Carlo realization of our YFS methods as they relate to YFS3.

Specifically, for a process such as $e^+e^- \to f\overline{f} + n(\gamma)$, we have from Refs. [5, 6], the fundamental differential cross section

$$\begin{aligned} d\sigma_{\text{YFS}} &= \exp\left\{2\alpha\,\mathrm{Re}\,B + 2\alpha\widetilde{B}\right\}\sum_{n=0}^{\infty}\int\prod_{j=1}^{n}\frac{d^3k_j}{k_j^0}\int\frac{d^4y}{(2\pi)^4} \\ &\times\; e^{iy(p_e+p_{\bar{e}}-p_f-p_{\bar{f}}-\sum_j k_j)+D(y)}\,\overline{\beta}_n(k_1,\ldots,k_n)\frac{d^3p_f d^3p_{\bar{f}}}{p_f^0 p_{\bar{f}}^0} \end{aligned} \tag{1}$$

where

$$D(y) = \int\frac{d^3k}{k^0}\widetilde{S}(k)\,\left(e^{-iyk} - \theta(k_{\max} - k^0)\right), \tag{2}$$

$$2\alpha\widetilde{B} = \int_{k^0\le k_{\max}}\frac{d^3k}{k^0}\widetilde{S}(k), \tag{3}$$

$$\begin{aligned} B &= \frac{-i}{8\pi^3}\int\frac{d^4k}{k^2 - m_\gamma^2 + i\epsilon} \\ &\times\;\left[-\left(\frac{-2p_e - k}{k^2 + 2k\cdot p_e + i\epsilon} + \frac{-2p_{\bar{e}} + k}{k^2 - 2k\cdot p_{\bar{e}} + i\epsilon}\right)^2 + \cdots\right], \end{aligned} \tag{4}$$

with

$$\widetilde{S}(k) = \frac{\alpha}{4\pi}\left[-\left(\frac{p_{\bar{e}}}{k\cdot p_{\bar{e}}} - \frac{p_e}{k\cdot p_e}\right)^2 + \cdots\right]. \tag{5}$$

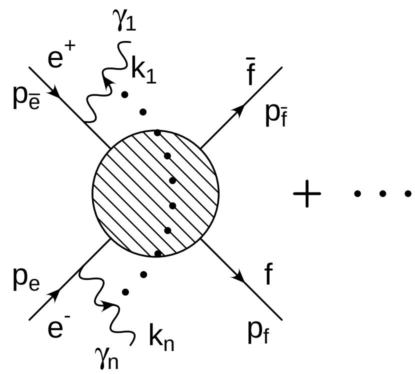

Fig. 1: The process $e^+e^- \to f\overline{f} + n(\gamma)$, with $n(\gamma)$ radiation from both the initial and the final state. Here, $f = e, \mu, \tau, u, d, s, c, b$ and p_A is the four-momentum of fermion A.

Here, the kinematics is that illustrated in Fig. 1, m_γ is the photon infrared regulator mass, and $\bar{\beta}_n$ are the YFS hard photon residuals defined in Refs. [5, 6], for example.

In YFS3 [3], two of us (S.J. and B.F.L.W.) have realized (1) via Monte Carlo methods for the case $f \neq e$ for both $n(\gamma)$ radiation from the initial state and $n(\gamma)$ radiation from the final state, with the hard photon residuals $\overline{\beta}_{0,1,2}$ implemented in the respective MC to $\mathcal{O}(\alpha^2)$ at the leading log level. Thus, the $\mathcal{O}(\alpha)$ contributions to $\overline{\beta}_{0,1,2}$ are exact and the $\mathcal{O}(\alpha^2)$ contributions are correct to the leading log level. It follows that, in a special region of the event phase space for events of the L3-type, it is necessary to check that the leading-log $\mathcal{O}(\alpha^2)$ approximation for the respective hard-photon effects is indeed accurate to the desired level of accuracy. It is this issue that we discuss in our following analysis.

3 Comparison of YFS3 and Exact $\mathcal{O}(\alpha^2)$ Results for L3-Type Events

In this section, we compare the exact $\mathcal{O}(\alpha^2)$ results in Ref. [4] for the process $e^+e^- \to l\bar{l} + 2\gamma$, restricted to the L3-type phase space cuts as they are given in Ref. [1], with those predicted by YFS3. Here, we emphasize immediately that, due to the wide angles of the photons with respect to the charged par-

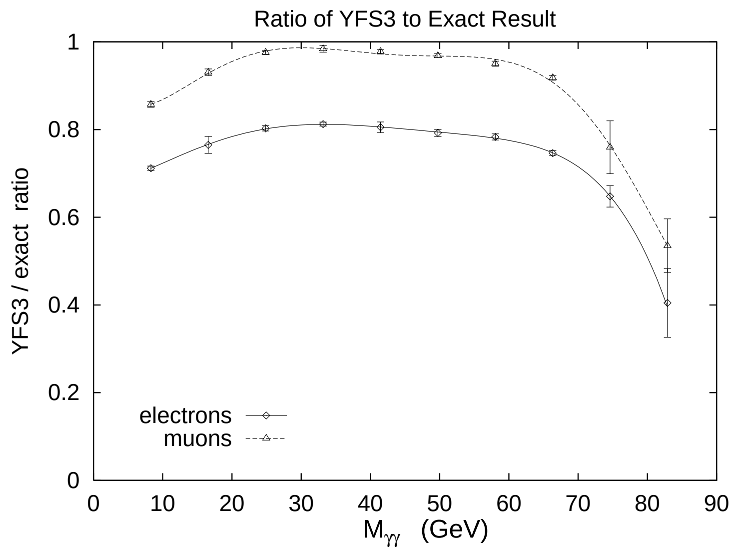

Fig. 2: The ratio of the YFS3 di-photon mass distribution to the exact $\mathcal{O}(\alpha^2)$ mass distribution for both $e^+e^-\gamma\gamma$ and $\mu^+\mu^-\gamma\gamma$ final states.

ticles, the effect of radiative corrections on the Z^0 line shape has been taken into account properly in YFS3, and this amounts to an over-all normalization correction to the cross section for L3-type events. Upon removing this Z^0 line shape effect, we are left with a comparison of the YFS3 two hard photon distributions in the L3-type events phase space with the analogous distributions as given by the exact $\mathcal{O}(\alpha^2)$ result. It is this comparison which we now present.

Specifically, we focus on the ratio of the YFS3 two hard photon leading log matrix element squared and the exact $\mathcal{O}(\alpha^2)$ two hard photon matrix element squared in the L3-type events phase space by plotting this ratio as a function of $M_{\gamma\gamma}$, the respective di-photon invariant mass, in such L3-type events. This we do in Fig. 2 for the cases $e^+e^- \to e^+e^- + 2\gamma$ and $e^+e^- \to \mu^+\mu^- + 2\gamma$. We see that, indeed, our YFS3 matrix element squared is within 78% of the exact $\mathcal{O}(\alpha^2)$ result for the $e^+e^- \to e^+e^- + 2\gamma$ case in the 60 GeV regime, and is within 94% of the exact $\mathcal{O}(\alpha^2)$ result in the $e^+e^- \to \mu^+\mu^- + 2\gamma$ case. Alternatively, we plot in Figs. 3 and 4 (for the $e^+e^-\gamma\gamma$ and $\mu^+\mu^-\gamma\gamma$ cases respectively) the di-photon mass distribution in the L3-event phase space for

the exact $\mathcal{O}(\alpha^2)$ and YFS3 two hard photon matrix elements squared, both (a) as $d\sigma/dM_{\gamma\gamma}$, and (b) as a histogram of the number of expected events versus $M_{\gamma\gamma}$ for 27 pb^{-1} of integrated luminosity. Also shown in Figs. 3(b) and 4(b) are the MC results from the L3 paper, Ref. [1], which are just the YFS3 results, of course. We conclude that, in all cases in Figs. 3 and 4, there is good agreement between our exact $\mathcal{O}(\alpha^2)$ expectations and those results generated by YFS3.

Recently, all LEP collaborations have searched for L3-type events. The results of their search are discussed in Ref. [2]. Here, we note that, in the regime of $M_{\gamma\gamma}$ between 50 GeV and 80 GeV, the LEP collaborations find 15 events in the L3-type 2γ phase space, and YFS3 predicts 9. The probability that this is a statistical fluctuation is 1.9%. What we can say here is that the statistical effects in the YFS3 comparison with data is indeed the dominant source of uncertainty in that comparison. Thus, we urge the experimentalists to strive for more data so that the nature of these observations can be clarified.

4 Conclusions

We have analyzed the L3-type $l\bar{l}\gamma\gamma$ event high di-photon mass spectrum in YFS3, the second order leading log YFS-exponentiated final + initial state $n(\gamma)$ radiation event generator, in comparison to the exact $\mathcal{O}(\alpha^2)$ prediction as determined by the results in Ref. [4]. We find good agreement between these two independent calculations of the respective spectra. This agreement means that the use of YFS3 to estimate the probability that the observed L3-type events at LEP are a QED fluctuation does not suffer from an unknown physical precision error associated with its use of $\mathcal{O}(\alpha^2)$ leading-log matrix elements for hard 2-photon emission into the respective L3-type $l\bar{l}\gamma\gamma$ phase space.

We want to note that a comparison of YFS3 with the $\mathcal{O}(\alpha^2)$ exact results in Ref. [7] has also been carried out [1, 8] and it agrees with our findings. The way is open to incorporate the exact $\mathcal{O}(\alpha^2)$ matrix element for the L3-type $l\bar{l}\gamma\gamma$ event phase space into YFS3 if the statistics on these events would be increased to require such accuracy in the YFS3 predictions. We encourage the LEP experimentalists to strive for such an increase in L3-type $l\bar{l}\gamma\gamma$ event statistics.

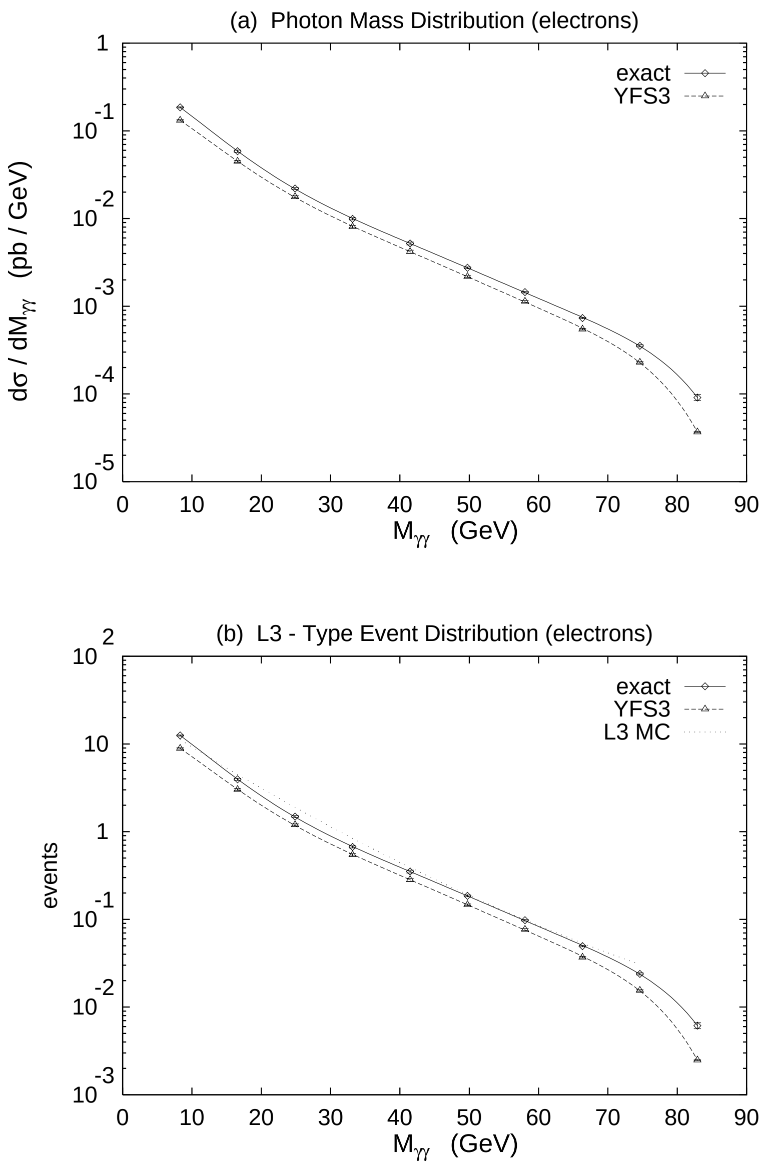

Fig. 3: Results for $e^+e^-\gamma\gamma$ final states. Graph (a) shows the photon mass distribution obtained using YFS3 and the exact $\mathcal{O}(\alpha^2)$ matrix elements. Graph (b) shows the same results normalized to give the number of events expected for a total integrated luminosity of 27 pb^{-1}, together with a dotted line showing the YFS Monte Carlo results used by the L3 Collaboration [1].

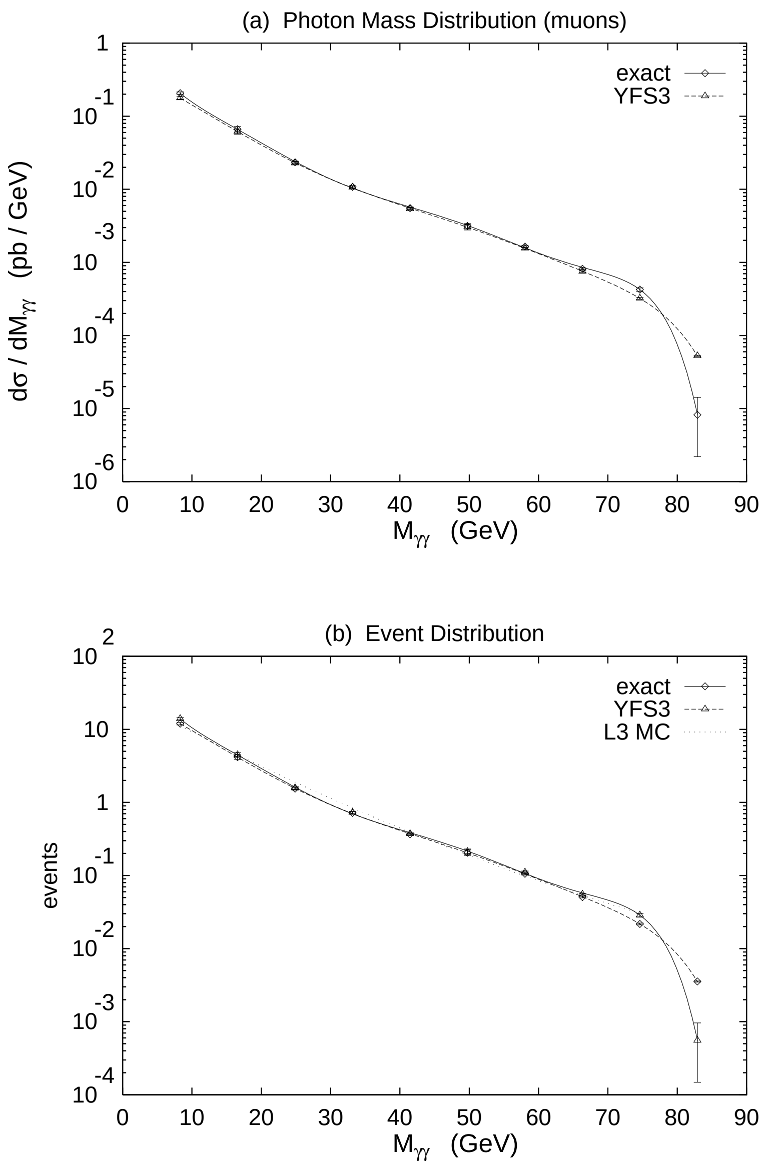

Fig. 4: Results for $\mu^+\mu^-\gamma\gamma$ final states. Graph (a) shows the photon mass distribution obtained using YFS3 and the exact $\mathcal{O}(\alpha^2)$ matrix elements. Graph (b) shows the same results normalized to give the number of events expected for a total integrated luminosity of 27 pb^{-1}, together with a dotted line showing the YFS Monte Carlo results used by the L3 Collaboration [1].

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